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Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback

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Abstract
The purpose of this study is to conduct a usability evaluation in order to investigate the actions and behaviors of human operators as they interact with a coordinated excavator controller with haptic feedback, and to identify potential usability problems that may confront operators as they interact with this new excavator interface. Traditional excavators usually use levers and pedals as the interface for operator control. However, with advances in computing power, it is possible to incorporate force feedback, or haptics, into the operator interface. The haptic interface is expected to provide force feedback to operators to give a sense of 'feel' to operators as they interact with the excavator through the use of the haptic Phantom device and, therefore, assist operators in performing their tasks more efficiently and effectively. This research aims to identify potential usability problems that may confront users, and to provide appropriate design suggestions to the design team. Results from the study showed that, users find the coordinated excavator controller to be intuitive, easy to learn and easy to use. Several usability issues were also identified, and appropriate design modifications were recommended.

Keywords: Haptics feedback, excavator controller interface, usability, usability evaluation

1 Introduction
Fluid power refers to the technology that exploits the properties of fluids to generate, control, and transmit power by pressurizing the fluid. Fluid power could be hydraulic or pneumatic. Hydraulic is generated using liquids (i.e. mineral oil or water) while pneumatics is generated using gas (i.e. air or another inert gas). Since the 1940's, fluid power has been used effectively by combining it with other technologies through the use of sensors, transducers, and microprocessors to provide power for a variety of industries. Several industries have benefited greatly from advances in fluid power technology. These include agriculture, construction, manufacturing, mining, transportation, aerospace, etc. One such machine that has wide applications in the construction, agricultural, and transportation industries is the excavator: an earthmoving machine powered by hydraulics. It consists of a digging bucket attached to the end of a movable, articulated arm/boom that can be used to tackle a wide variety of trenching, loading, scooping, filling, and leveling chores that would otherwise require multiple machines or considerably more time. A Bobcat excavator is shown in Figure 1. Although it is a work horse of choice and a fixture at most construction sites, operating the excavator is not an easy task. First, operators have to manipulate the excavator by actuating manual levers which then act on the flow control valves. Operators, therefore, are required to solve the inverse kinematic

relationships between lever displacement and bucket trajectory in order to efficiently operate the excavator [1], a task that requires extensive training time and experience to accomplish. Secondly, excavators operation presents concerns about operator ergonomics, visibility and comfort.

Figure 1: A backhoe excavator

A good design must ensure that operators have unrestricted sightlines, perform tasks comfortably, and be in-control of the machine [2]. However, due to constraints of current designs, operators have to be trained for quite some time before they are able to comfortably operate the machine and solve the inverse kinematic relationships subconsciously. Since the only feedback available to the operator is the observed bucket speed, the engine's response to load, and/or pressure waves propagated back to the user's hand, it is usually not easy for novice operators to have a "feel" for the non-intuitive lever motions [1].

As a result, construction companies often have to hire or contract professional operators for even the simplest earthmoving tasks at a high cost and inconvenience. To overcome this problem, the haptic interface is being considered as an alternative to the traditional direct manipulating control levers. Since human cognitive processes and perception is build largely upon multimodality, a proper combination of different interface components will result in a flow of information on several parallel channels and has been shown to enhance effectiveness of interaction [3]. By making use of the haptic control interface instead of the traditional levers and pedals, excavator operators will be freed from solving the inverse kinematic relationships, thus, resulting in a more efficient and effective task performance and shortened training time for novice operators [4]. Although the coordinated controller interface with haptic feedback promises reduced mental workload and improved operator performance over the traditional lever/pedal interface as discussed above, its usefulness (usability) as a control interface for the excavator has not been fully explored partly because the technology is still being developed. The concept of using haptic interface to control the excavator is currently being tested in a testbed at Georgia Institute of Technology where a coordinated excavator controller interface with haptic feedback is under construction [1-2]. The haptic input device is PHANToM 1.0 originally designed by Massie and Salisbury in 1994 and subsequently commercialized by SensAble Technologies [5].

The goal of this study was to conduct a usability testing of the excavator interface with haptic feedback currently being developed by a Mechanical Engineering team at the Georgia Institute of Technology. The development of the haptic-controlled excavator interface is part of an ongoing collaborative effort by the Center for Compact and Efficient Fluid Power (CCEFP) to develop safe, efficient and easy to use interfaces for applications in fluid power systems. The usability testing aims to help investigators identify potential usability problems that may confront users, and to provide appropriate design suggestions to the design team. Usability of an interface refers to the ease with which users are able to use the interface to accomplish the required task (or a measure of a product's potential to accomplish the goals of the user). According to [6], a system's acceptability has two dimensions: practical acceptability and social acceptability. Practical acceptability is defined by usefulness, cost, reliability, compatibility etc. Further, usefulness has two dimensions, utility and usability. Usability can be defined by 5 main attributes. These are *learnability, efficiency, memorability, error rate,* and *satisfaction*. Figure 2 represents the attributes of a system's acceptability as well as the different dimensions of usability. Usability of a system usually has some tradeoff with utility of the system. While system utility describes whether or not a system performs as designed (system functionality), system usability describes whether or not the user is able to successfully use the system as designed (usefulness). Usability tests are usually designed to test real users in order to get direct information about how they interact with the system and the problems they will encounter along the way. A valid usability test, thus, yields valuable information similar to what will be expected if the product/interface were to be used outside laboratory settings. To ensure test validity, it is important to design tests, which require the users to perform tasks that are comparable to the actual users and the tasks they perform.

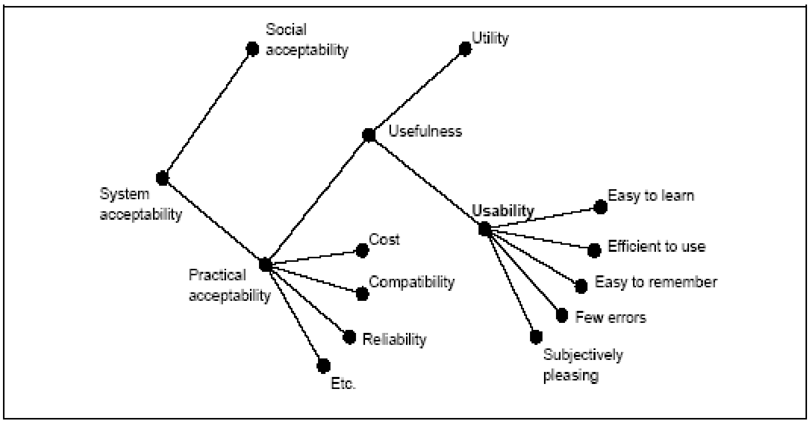

Figure 2: A model of the attributes of system acceptability

2 Methodology

Twenty students (14 males and 6 females) between the ages 21-31 (mean age = 24, standard deviation = 2.37) were recruited from the Georgia Institute of Technology to take part in the usability testing. The volunteers were made up of 14 Caucasians, 5 Asians, and a Hispanic. 43% of participants had some experience using a joystick and playing videogames, and 57% did not. Three participants had prior experience using the haptic interface while the rest had no such experience.

2.1 Equipment

The equipment for the experiment consisted of 3 computers, a Bobcat excavator cabin, a Phantom Premium 1.0A haptic device, a 52'' Samsung flat screen LCD and 2 video cameras.

The C++ and MatLab programming that run the simulation was developed by Mark Elton. The three computers used for the simulation are connected via a local network. Computer number one interfaces with the Phantom, the second computer runs the graphical display, and the third runs the excavator dynamics simulation. The graphics was then displayed on the 52’’ Samsung flat screen mounted in front of the excavator cabin to simulate the environment in which the tasks were being performed. The Phantom device sat towards front right corner of the cabin and had 6 degrees of freedom in total: up-down, left-right, front-back, and a rotating stylus with 3 degrees of freedom. The two video cameras were used to record both audio and video images. Figures 3(a), (b) show the equipment set up for the experiment.

2.2 Task

Using the stylus of the Phantom Premium device, participants were instructed to dig dirt from the marked trench area and dump the dirt into two bins located to the left and right of the trench. Three tasks were assigned. Task #1 was to fill bin #1 alone, task # 2 was to fill bin # 2 alone, and task #3 was to fill both bins. These tasks were chosen based on task analysis results that identified moving, digging and dumping/pilling as common tasks often performed by excavator operators. The order in which tasks 1, 2 and 3 were performed was randomized among participants. Full bins turned green along with an audio alert so participants knew the task was completed. Participants performed two sessions of the experiment. In each session, they did all three tasks in the same order. During the experiment, participants were asked to think aloud to enable their thought process to be captured as they went through the assigned tasks.

2.3 Procedure

Upon arrival, participants were briefed on the purpose of the study and asked to read and sign a consent form. A pre-test questionnaire was administered to collect demographic information as well as participants’ experience in playing videogames and operating earthmoving equipment. A short demo of the simulation was given, and participants were given a few minutes to familiarize themselves with the simulator. Questions about the simulator and controls from the participants were answered by the experimenter before the test started. All participants were informed that the experiment would be video-taped for further analysis. Upon completion of the tasks, the participants were thanked, debriefed, and asked to complete a post-test questionnaire. Participants were asked about their experience using the haptic-controlled excavator interface, their comfort level, and for their comments and suggestions. Overall, it took about 1 hour to complete the test. Figure 3 shows a participant taking the test.

Figure 3: A participant taking the test

2.4 Data Collection

Objective data such as task completion time, mean number of scoops required to fill up a bin, as well as the number scoops that were dropped outside the bins were recorded. Subjective data such as user opinion and satisfaction were also collected through questionnaires.

3 Results

For all participants, the mean task completion time was 132.86s with std. dev of 25.29s. A task in this study is defined as the time it takes a participant to completely fill up one bin with dirt. The fastest participant took an average of 74.01s to complete task, while the slowest participant took an average of 170.99s to complete task. The completion times for all participants is shown in Figure 4 below. A summary of responses to post-test questionnaire is also shown graphically in Figure 5.

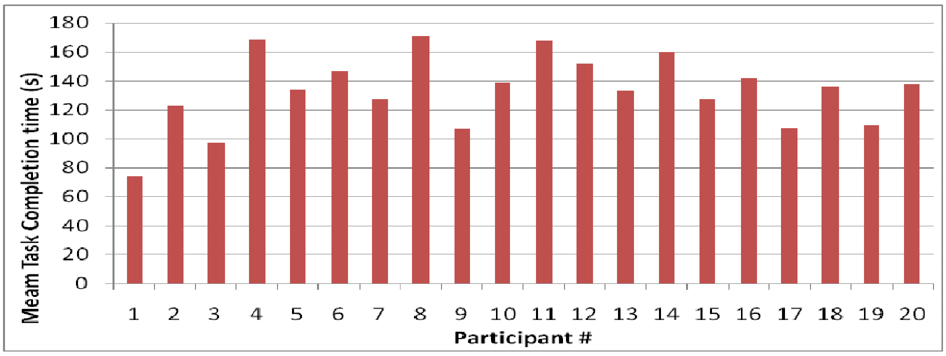

Figure 3: Task completion time for participants

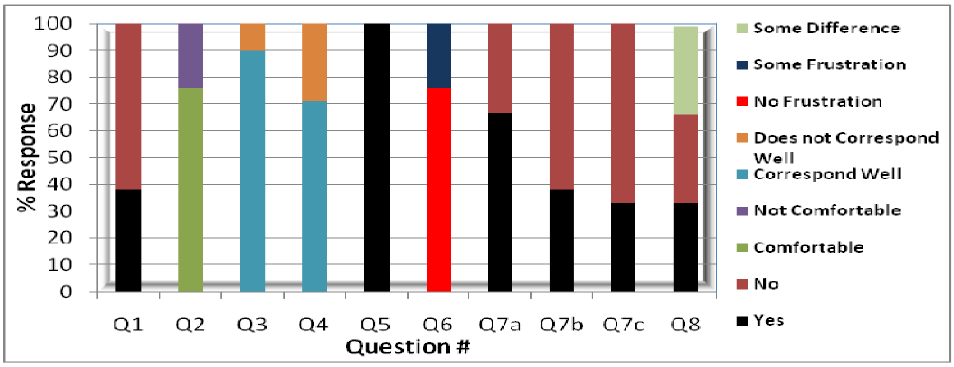

Figure 4: Summary of responses to post-test questionnaire

The usability attributes of *learnability*, *efficiency*, *memorability*, *error rate/prevention* and *user satisfaction* were rated based on participants' responses and other feedback received from participants. On learnability, all participants judged the haptic controlled interface as being easy to learn. Similarly, all participants felt tasks were easy to performed, though some indicated that they found the interface a bit confusing initially. Even with initial confusion, they were able to learn the system fairly easily with little practice. Since nearly all participants were novice users, the design implication is that the haptic controlled interface is generally easy to learn and use, and novice users can learn to use it within a reasonably short period of time with some improvement.

When asked if they were able to efficiently carry out the assigned task using the haptic interface, most participants felt the efficiency of the interface could be improved. First, participants complained that the phantom device was too sensitive and stiff. Either way, it made control of the bucket as well as the movement of boom difficult. About 30% of participants felt that rotating the stylus of the Phantom device did not correspond well enough with open and close movements of the bucket, further most participants reported that the bucket did not respond very well to the rotation command of the stylus, or that the bucket opened/closed while the user had not given any rotation command. The combined effect of the stiffness and the general awkwardness of the phantom control resulted in fatigue and stress in the shoulder and wrist of participants. This prevented users from performing the task in a more efficient manner.
On memorability of the system, most participants felt the interface was easy to remember. It was observed that three participants who have had a previous experience with the haptic interface had average task completion time of 117.13s compared to the overall task completion time of 132.86s for all participants. Clearly, those who had prior experience with the interface were able to complete the tasks faster because they relied on their prior knowledge. A common concern expressed by participants was that the clockwise and counterclockwise movement of the stylus did not correspond well with bucket open/close motion. As a result, users sometimes had to rotate the stylus multiple times in order to open or close the bucket. This led to a situation where participants forgot which direction of rotation corresponded to bucket open or close movement.

On error prevention, most participants felt the high sensitivity and stiffness of phantom device as well as the general lack of steady control made it difficult for users to avoid errors. For example, an operator might want to stop the excavator immediately in case of emergency; however, he might not be able to do this due to the lack of steady control. Also, because the excavator sometimes did not respond well to operator commands, operator may not be able to completely control the excavator at all times to prevent errors from occurring. Further, introducing start and stop points (limit points) on stylus rotation will help reduce operator frustration and improve performance on tasks. For example, when bucket is fully open, it should correspond to the limit of rotation of the stylus in one direction, likewise, when it is fully closed, it should correspond to the limit of rotation of the stylus in the other direction. This way, a point in rotation will be reached when operator knows the bucket is fully opened/extended or when bucket is fully closed/retracted. In other words stylus rotation should stop when bucket is fully open or closed (stylus should rotate 180° so it is exactly mimics the bucket).

4 Discussion

The results from the usability testing of the haptic controlled excavator interface show that, the system is very intuitive and given the necessary modifications, could provide a breakthrough on how excavators of the future are controlled and operated. When asked about their impression of the interface after testing, most participants felt it was intuitive, easy to learn and easy to use. These attributes may give the coordinated excavator controller with haptic feedback some advantages over the traditional lever/joystick controlled interface, as operators will find it more intuitive, easy to learn and use, and thus, reduce operator training period and associated costs. The presence of appropriate force feedback may also assist operators perform much more efficiently, as they will be alerted to the presence of buried pipelines/cables and, thus, avoid causing damage to them.

In spite of the benefits that the coordinated excavator interface might bring, several potential problems were identified from the usability testing that need to be addressed. Some of the potential problems identified are summarized in Table 1 and have been assigned severity ratings based on Nielson (1993) Severity Ratings.

Table 1: Usability Problems Identified, their Severity Rating and Design Principle Violated

Usability Problem	Severity Rating	Design Principle Violated
1. Excavator too sensitive/stiff to be properly controlled with phantom device/stylus. This may frustrate users and cause fatigue in shoulder and wrist	3	System flexibility and efficiency of use
2. Operators unable to steadily control excavator. Users found it difficult to maintain control of the excavator with the phantom/device stylus	3	Lack of user control and freedom, lack of flexibility and ease of use
3. Difficulty in maintaining hand-eye coordination. Due to stiffness and general awkwardness of interface, hand-eye coordination becomes stressful	3	System flexibility and efficiency of use
4. Bucket movement is not properly synchronized with rotation of stylus (bucket movement responds poorly to stylus command/rotation)	3	Lack of match between system and real world
5. No difference between an empty and a full bucket, also no feeling of contact between the bucket and objects (ground, bin, pipe, trench walls, etc)	3	Match between system and real world
6. Difficulty understanding the mapping between excavator and phantom device. Mapping of excavator arm to phantom device is reversed	3	Lack of natural mapping
7. Lack of appropriate arm rest/support may lead to fatigue in shoulder and elbow	3	Operator/workspace ergonomics
8. Restricted workspace around phantom	3	Operator/workspace

device may interfere with task performance		ergonomics

Recommendations

In order to make haptic controlled excavator interface more user friendly and to ensure that operators are able to use it more efficiently, it is recommended that attention be paid to the usability problems identified and enumerated in Table 1. First, the sensitivity/stiffness of the phantom device needs to be improved. This will result in a steadier operator control over the excavator, thus provide the operator with the freedom and control required to perform efficiently. Second, bucket movements need to be properly synchronized with phantom device/stylus rotation. In other words, bucket should have a start and stop points (limit of rotation points) on the stylus such that stylus rotation stops when bucket is fully open or fully closed. This will eliminate the situation where operators sometimes have to rotate stylus multiple times in order to open or close bucket. Third, providing some form resistance or force feedback to signify the weight of load may help operators differentiate between an empty bucket and a full/loaded bucket. Further, the provision of a proper arm rest/support would help reduce arm and shoulder fatigue. Also, it is important that adequate workspace is provided around the phantom device to ensure there is no obstruction/interference so operators can perform their task freely and efficiently.

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